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Study of the relationship between flatwise and edgewise moduli of elasticity of sawn timber as a means to improve mechanical strength grading technology

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In most of the strength grading machines for sawn timber, the flatwise bending modulus of elasticity (MOE) of timber pieces is measured. Employing regression functions, their edgewise MOE is estimated on the basis of the flatwise MOE and the edgewise bending strength of the weakest part of each piece is calculated to allocate each piece to a standardised strength class. With regard to improvements in the accuracy of timber strength grading machines, it was studied to which extent structural wood characteristics and grading parameters affect the relationship between flatwise and edgewise bending MOE. Edgewise and flatwise MOE have been determined both in knotty and in knot-free sections of boards of Norway spruce. The flatwise MOE was determined in a three-point bending test as it is typically employed in strength graders. The edgewise MOE was determined in a four-point bending test. Additionally, the MOE and density distributions over the timber cross sections were determined to model the total MOE under consideration of these distribution patterns. Shear deformation accounts for a substantial portion of the difference between flatwise and edgewise MOE. The effect of knots on the MOE could not be defined precisely. Growth ring structure and juvenile wood in the boards lead to 5 to 10% lower flatwise MOE values as compared to the edgewise MOE.

Untersuchungen des Verhältnisses von flachkant zu hochkant ermitteltem Elastizitätsmodul von Schnittholz zur Verbesserung der maschinellen Festigkeitssortierung

In Schnittholzsortiermaschinen, die nach dem Prinzip der elastischen Durchbiegung arbeiten, wird der Elastizitätsmodul des flachkant belasteten Schnittholzes bestimmt. Mithilfe von Regressionsfunktionen werden daraus der Elastizitätsmodul und die Festigkeit des Schnittholzes bei Hochkantbelastung zur Klassifizierung in Festigkeitsklassen abgeschätzt. Im Hinblick auf die Optimierung der mechanischen Schnittholzsortierung wurde untersucht, inwieweit Struktureigenschaften des Holzes und Prüfbedingungen das Verhältnis zwischen den Elastizitätsmodulwerten einzelner Bohlen bei Flachkant- und bei Hochkantbelastung systematisch beeinflussen. An astfreien und astigen Abschnitten von schwedischen Fichtenbohlen wurden statische Biegeversuche in Hochkant- und Flachkantrichtung vorgenommen und die Rohdichte- und Steifigkeitsvariationen über den Querschnitt der Bohlen untersucht, um die Bohlensteifigkeit rechnerisch abzuschätzen. Flachkantbiegeversuche wurden wie in Sortiermaschinen üblich mit Dreipunktbelastung durchgeführt, hochkant wurden die Bretter im Vierpunktversuch gebogen. Der Anteil der Schubverformungen bei der Flachkantbiegung bestimmt die Differenz zwischen flachkant und hochkant ermitteltem Elastizitätsmodul maßgeblich. Die Auswirkungen von Ästen auf die Steifigkeit konnte nicht klar beschrieben werden. Aus Jahrringstruktur und Jugendholz in den Brettern ergaben sich 5 bis 10% niedrigere Flachkant-E-Modulwerte verglichen mit den hochkant ermittelten Werten.

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1 Strength grading of structural sawn timber

As a structural material, wood faces the competition of steel, concrete, aluminium, and other materials in various applications. In comparison with the other materials, wood exhibits a wider variability of decorative and physical properties. On the one hand, architects and builders appreciate the optical appearance of wood in load-bearing and decorative applications; on the other hand, the variability in its mechanical properties makes the technical design of wooden structures more complex as compared to materials with precisely defined elastic and strength properties. In an interview with more than 500 architects, Glos (1991) revealed that the variability of the mechanical properties, the susceptibility to attack by micro-organisms, and the dimensional instability of wood are regarded as quality defects which limit the utilisation of wood as an engineering material considerably. The architects claimed precise design values and good workability at reasonable cost of wood in structural applications.

With regard to design values, these requirements can be fulfilled through an application-oriented strength grading of structural sawn timber. Visual or machine strength grading of sawn timber into strength classes has proved to render good results in e.g. Scandinavia, Great Britain, North America, New Zealand (Glos and Schulz 1980, Johansson and Johansson 1987). In most of these regions, wood is a common material in construction of family homes and other buildings.

In Germany, grading of structural sawn timber into strength classes has only recently been standardised in connection with the latest review of DIN 4074 (Radovic 1990). The characteristic properties of timber in different German strength classes are defined in the German National Application Document (NAD) for the European timber design code (Eurocode 5).

According to the grading standards for structural timber, sawn timber may be graded visually or by machine

into strength classes. Criteria for visual grading are usually the growth characteristics, biotic and mechanical wood defects, cracks, deformation, the sawing pattern, and the accuracy of timber dimensions (Kessel and Sandoz 1989, Steiger 1991). Based on the classification of these characteristics, MOE and strength of sawn timber in static bending are estimated. Alternatively, sawn timber may be tested in mechanical and/or radiation-based or other types of non-destructive strength grading machines. According to DIN 4074, the machine strength grading substitutes for some of the visual grading characteristics and thus facilitates the grading process for the grader.

In most structures, e.g. roof trusses, floor joists, wooden members are bent edgewise. For specific application, e.g. scaffolding planks, the flatwise bending MOE and strength may be critical.

Most of the strength grading machines for sawn timber (Cook Bolinder, Computermatic, Euro-Grecomat systems; detailed descriptions are provided by Tebbe 1987, Boström 1994, Palm 1995, Görlacher 1995) are bending machines through which the sawn timber is fed. In these machines, the flatwise modulus of elasticity (E_{flat}) in bending of sawn timber up to 75 mm thickness is measured with a span of about 90 cm (three-point-loading) at a relatively high accuracy as compared to conventional static bending test machines. Subsequently, their edgewise MOE is estimated on the basis of the flatwise MOE, and finally the edgewise bending strength (modulus of rupture, MOR) of the weakest part of each piece of timber is calculated to allocate the sawn timber to standardised strength classes. Alternatively, a regression function with MOR as the dependent and E_{flat} as the independent variable may be employed to allocate timber to strength classes.

Such procedures are necessary because the direct assessment of the edgewise timber MOE would require much larger a span between the supports in the strength grading machine and much higher forces applied on the sawn timber. The cost of the equipment would rise to an unacceptable level and, due to the wide span of the machine, long portions at both ends of the timber pieces could not be examined. The direct assessment of bending strength would involve destructive testing of the sawn timber which would be unacceptable as a grading method. The estimation of the edgewise MOE and bending strength values as described above implies two inaccuracies which have to be minimised:

1. The structural features of wood as a natural material lead to anisotropic and inhomogeneous physical properties of timber. With regard to its properties in bending, this means that for instance growth ring orientation and width, slope of grain, density distribution, knots, and other localised inhomogeneities (such as pitch pockets, cracks, etc.) in timber result in differing MOE and strength in flatwise and edgewise bending. Johansson et al. (1992) obtained a difference of 23% between the moduli of elasticity in edgewise bending according to EN 408 and flatwise three-point-bending in a grading machine for 58×120 mm^2 Norway spruce timber. After correction for shear deformation, a difference of 7 to 12% remained.
2. Even if the edgewise MOE of sawn timber would be determined correctly, this MOE would not enable a precise prediction of the edgewise bending strength as the structural inhomogeneities of the wood exert differing influences on MOE and ultimate strength, respectively. Endersby (1969), Glos and Schulz (1980), and Anonymous (1986) concluded from literature surveys that correlation coefficients of the order of 0.7 to 0.8 are typical for the relationship between MOE and strength. Hence, the variation of the MOE only accounts for about half of the variation of strength of the sawn timber.

In Sweden, the setting values for strength grading machines for sawn timber from 38 to 63 mm thickness are exclusively based on Brundin's (1981) regression model. This model results in relatively low estimations of the edgewise timber MOE and bending strength, especially for thicker sawn timber dimensions (Figure 6 and Figure 7, Wormuth 1993). With respect to the safety of load bearing structures, a careful estimation of timber strength may be useful but it reduces the yield of highly-priced structural sawn timber providing high load-bearing capacity considerably.

2
Aim of the study

It was the aim of this study to contribute to a better understanding of the structural wood characteristics which affect the relationship between flatwise and edgewise MOE in order to improve the accuracy of sawn timber strength grading.

Considering the fact that machine strength grading has recently been implemented into DIN and EN standards and it will therefore gain increasing importance in most of the EN countries through international trade in structural sawn timber, the results of this study may contribute to an improved certification and setting of strength grading machines. Reliable grading of sawn timber into high strength classes may enable more efficient structural design on the one hand and adequately high prices for sawn timber of high MOE and strength.

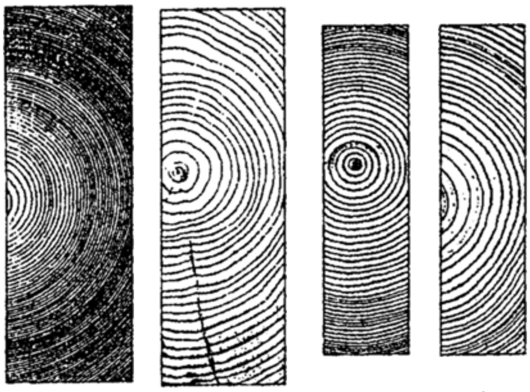
3
Material and methods

The flatwise MOE profile over the full length of 40 boards of Norway spruce (*Picea abies*) of two cross sectional dimensions, 45×170 and 67×195 mm^2 and lengths varying between 4.2 and 5.45 m was assessed with a Cook Bolinder strength grading machine to select characteristically different timber pieces. In previous studies (Brundin 1981, Johansson and Johansson 1987, Johansson and Claesson 1989, Johansson et al. 1992, Boström 1994), the good correspondence of the flatwise MOE values obtained from the Cook Bolinder system and the flatwise MOE determined in a conventional static three-point bending test has been shown.

13 boards (8 boards 45×170, 5 boards 67×195 mm^2) showing characteristic differences in growth ring structures, pith positions, and knot patterns (Figure 1)[1] were selected for the study.

One knotty and one clear specimen of 40 cm length were marked on each of the selected boards for comprehensive studies of the MOE and density distributions over the cross section of the boards. On each of the specimens the edgewise MOE was determined according to EN 408/ISO 8375 (four-point-loading) with a span-to-depth ratio of 18

[1]The sawn timber for this study was donated by Södra Timber AB, Växjö, and Limmared Skogar, Limmared, Sweden, which the authors gratefully acknowledge.



a b c d

Fig. 1a–d. Illustration of different types of boards: **a** constant growth ring width, pith outside the board; **b** variable growth ring width, lateral pith position; **c** variable growth ring width, central pith position; **d** variable growth ring width, pith outside the board
Bild 1a–d. Darstellung verschiedener Bohlenquerschnitte: **a** Jahrringbreite konstant, Markröhre außerhalb der Bohle; **b** Jahrringbreite variabel, Markröhre seitlich; **c** Jahrringbreite variabel, Markröhre mittig; **d** Jahrringbreite variabel, Markröhre außerhalb

Table 1. Basic characteristics of the specimens
Tabelle 1. Wichtige Eigenschaften der Versuchsbohlen

Specimen	Mean moisture content [%]	Mean growth ring width [mm]	Mean density ($\rho_{0/12}$) [g/cm^3]	Knot-area-ratio (KAR)
Board size 45 × 170 mm^2				
01	14.1	2.51	416	0.24
04	13.9	3.12	433	0.26
08	13.8	2.20	357	0.19
09	13.8	2.29	460	0.35
10	13.3	1.90	431	0.19
14	13.8	1.75	388	0.20
19	13.6	2.38	374	–
20	13.9	2.63	409	0.25
Average	13.8	2.35	408	0.17
Board size 67 × 195 mm^2				
21	12.0	2.05	393	0.18
23	10.6	3.39	357	0.31
25	11.5	1.43	435	0.13
34	12.2	1.17	441	0.12
35	12.1	1.53	433	0.10
Average	11.7	1.91	411	0.24

(hereinafter referred to as E_{edge}). Their flatwise MOE was examined in a static three-point bending test with a span of 900 mm equalling the span in the strength grading machines. Flatwise and edgewise bending tests were performed twice for each board section, both sides of the board being positioned on the compression and tension side, respectively. Actually, differences between the two flatwise and the two edgewise MOE values, respectively, obtained from each section were negligible. Hence, only average E_{flat} and E_{edge} values obtained from the two tests were used for further analysis.

Attempts were made to quantify the influence of knots, growth ring structure, and pith position in the timber on the accuracy of the edgewise bending strength estimation. For this purpose, the knotty and the clear specimens were sawn out of the boards. One 45 mm long part of each specimen was used to determine average density (ISO 3131), moisture content (ISO 3130), and growth ring width. The remaining part was reduced to 300 mm length, its cross-cut-section was photocopied and the knot-area-ratio (KAR) was determined for the knotty board specimens. KAR is the total projected knot area in relation to the total cross-cut-section (Figure 2, Table 1).

The short specimens were sawn longitudinally into 1980 sticks of 9 × 9 mm^2. For each stick, density and growth ring width were determined and their MOE was measured with ultra sonic pulses (device: Pundit by C.N.S. Electronics). The Pundit-device measured at a frequency of 54 kHz. A contact grease was used. The dynamic MOE was calculated according to

$$E_{dyn} = c_L^2 \cdot \rho \qquad \text{(Eq. 1)}$$

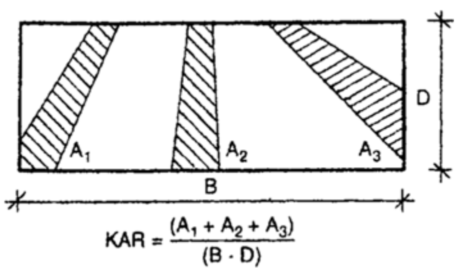
where c_L is the ultrasonic pulse velocity and ρ is the density of the stick.

For calibration purposes, the dynamic (E_{dyn}) and the static MOE in tension ($E_{t\ static}$) were determined on 70 specimens. In the static tension test, the rate of loading was adjusted to correspond to the conditions in the edgewise and flatwise bending tests. The relation between static MOE in tension and dynamic MOE was

$$E_{t\,static} = \frac{E_{dyn}}{1{,}056} \qquad \text{(Eq. 2)}$$

with a correlation coefficient of 0.92. On the basis of equations 1 and 2, a calibrated E_{dyn} of each stick was calculated.

The MOE values of the knotty and the clear sticks were employed in a calculation of the flatwise and edgewise MOE values for the entire clear and knotty board specimens, respectively, employing Steiner's formula (Figure 3, Equation 6). The MOE values calculated for each board section (hereinafter referred to as $E_{flat\ calc}$ and $E_{edge\ calc}$, respectively) were compared with the flatwise MOE determined in the three-point bending test and the edgewise MOE measured in the four-point bending test in the testing machine.



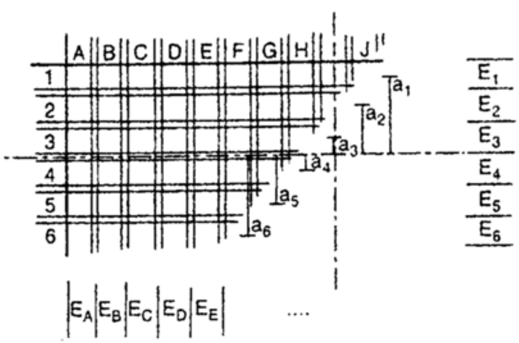
$$KAR = \frac{(A_1 + A_2 + A_3)}{(B \cdot D)}$$

Fig. 2. Example for the calculation of the knot-area-ratio (KAR)
Bild 2. Beispiel für die Berechnung des Astflächenverhältnisses (KAR)

4 Results

4.1 Static bending tests

The static bending tests (Table 2) show higher edgewise MOE as compared to the flatwise MOE for all specimens. The average difference is 22% for the knotty specimens of the 45 × 170 mm^2 and 49% for those of 67 × 195 mm^2 boards. For the clear specimens, the differences are slightly



$$E_1 = \frac{\sum_{i=A1}^{Q1} E_i}{17} \text{ [MPa]; accordingly for } E_2 \text{ bis } E_6 \quad \text{(Eq. 3)}$$

$$I_1 = \frac{(b \cdot d_1^3)}{12} + (b \cdot d_1 \cdot a_1^2) \text{ [mm}^4\text{]; accordingly for } I_2 \text{ bis } I_6 \quad \text{(Eq. 4)}$$

$$E_{flat\ calc} = \frac{\sum_{i=1}^{6} E_i \cdot I_i}{\sum_{i=1}^{6} I_i} \text{ [MPa]} \quad \text{(Eq. 5)}$$

Fig. 3. Scheme for the Calculation of the flatwise and edgewise moduli of elasticity, respectively. (N.B.: The precise position of the neutral axis has been taken into consideration.)
Bild 3. Schema zu Berechnung von Flachkant- ($E_{flat\ calc}$) und Hochkant-E-Modul ($E_{edge\ calc}$). (Anm.: Die genaue Position der neutralen Faser wurde berücksichtigt.)

smaller and the MOE values are slightly higher. The E_{edge}/E_{flat} ratio increases with increasing timber thickness which indicates a considerable influence of shear deformation on the total deflection in the three-point bending test and, hence, on the actual MOE value. The differences are in the same order as those reported by Boström (1994), but higher than those obtained by Burger and Glos (1995). E_{edge}/E_{flat} ratios are fairly similar for clear and knotty board specimens of one dimension.

Among the knotty board specimens, the E_{edge}/E_{flat} ratio increased with decreasing knot-area-ratio (Figure 4) which indicates that the knots reduced the difference between edgewise and flatwise bending MOE of the specimens. With increasing E_{edge}, the E_{edge}/E_{flat} ratio increases as well (Figure 5).

In Figure 6 and Figure 7 the actual regression functions for the MOE values determined in this study are compared with Brundin's (1981) function. Brundin's function establishes an E_{edge}/E_{flat} ratio of 1.27, approximately, which is only slightly smaller than the actual ratio for the small-sized timber but deviates considerably from the actual ratio for the bigger timber dimension. Due to this deviation of regression functions, the MOE of thick boards with high absolute MOE values is underrated in actual Swedish strength grading machines. The calculation of E_{edge} according to Brundin's function reduces the yield and the value of sawn timber with a high MOE.

Generally, the wide variation of the E_{edge}/E_{flat} ratio, specifically between individual boards of one dimension, indicates that the variation of the wood structure exerts a distinct influence on the MOE.

4.2
Distribution of density and MOE over the cross section of the board specimens

In order to study the relationship between structural characteristics of wood and the MOE of timber, the spec-

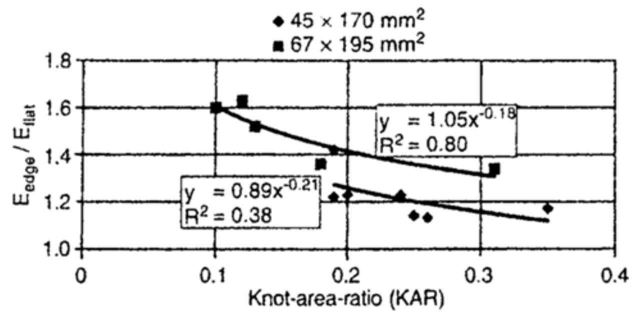


Fig. 4. Relationship between KAR and the E_{edge}/E_{flat} ratio
Bild 4. Zusammenhang zwischen KAR und dem E_{edge}/E_{flat}-Verhältnis

Table 2. Comparison of E_{flat} and E_{edge} as determined in static bending tests for clear and knotty specimens
Tabelle 2. Vergleich des Flachkant- (E_{flat}) und des Hochkant-Biege-E-Moduls (E_{edge}) von astfreien und astigen Proben

Specimen	Clear specimens			Knotty specimens		
	E_{flat} [MPa]	E_{edge} [MPa]	Ratio $\frac{E_{edge}}{E_{flat}}$	E_{flat} [MPa]	E_{edge} [MPa]	Ratio $\frac{E_{edge}}{E_{flat}}$
Board size 45 × 170 mm²						
01	11700	13650	1.17	11100	13650	1.23
04	12500	14750	1.18	11100	12550	1.13
08	11850	14850	1.25	10850	13250	1.22
09	14450	16050	1.11	12850	15000	1.17
10	14950	19950	1.33	13900	19700	1.42
14	12400	16300	1.31	11300	13900	1.23
19	11200	12700	1.13			
20	12250	14050	1.15	11050	12650	1.14
Average	12650	15300	1.20	11750	14400	1.22
Board size 67 × 195 mm²						
21	10600	13950	1.32	9400	12750	1.36
23	8800	11200	1.27	8050	10750	1.34
25	12550	17650	1.41	12350	18750	1.52
34	13200	21000	1.59	12650	20650	1.63
35	12700	18750	1.48	11700	18700	1.60
Average	11550	16500	1.41	10850	16300	1.49

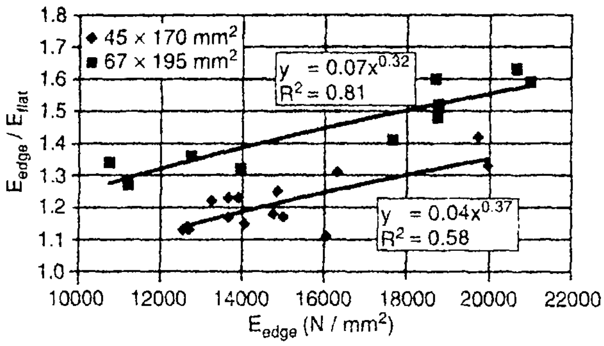


Fig. 5. Relationship between E_{edge} determined according to EN 408/ISO 8375 and the E_{edge}/E_{flat} ratio
Bild 5. Zusammenhang zwischen E_{edge} bestimmt nach EN 408/ ISO 8375 und dem E_{edge}/E_{flat}-Verhältnis

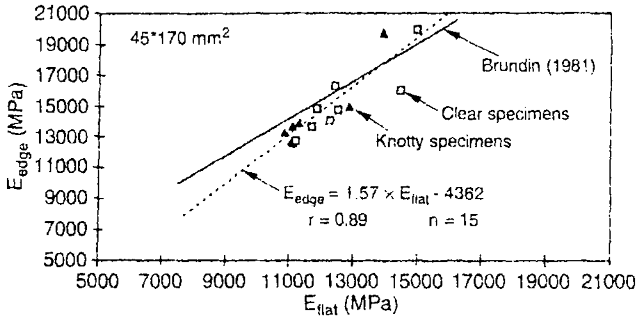


Fig. 6. Relationship between E_{flat} and E_{edge} in comparison with Brundin's function which is employed in Swedish strength grading machines; timber size 45 × 170 mm²
Bild 6. Zusammenhang zwischen E_{flat} und E_{edge} im Vergleich mit der von Brundin ermittelten Funktion, die in schwedischen Festigkeitssortiermaschinen angewandt wird; Bohlenquerschnitt 45 × 170 mm²

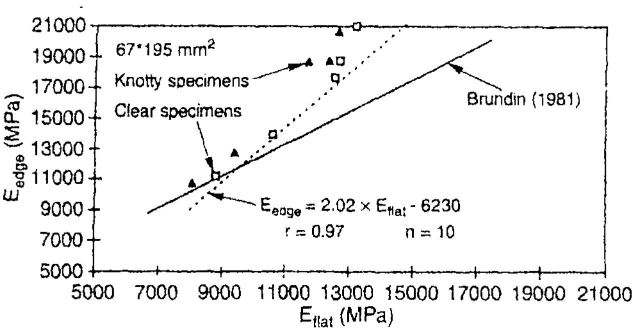


Fig. 7. Relationship between E_{flat} and E_{edge} in comparison with Brundin's function which is employed in Swedish strength grading machines; timber size 67 × 195 mm²
Bild 7. Zusammenhang zwischen E_{flat} und E_{edge} im Vergleich mit der von Brundin ermittelten Funktion, die in schwedischen Festigkeitssortiermaschinen angewandt wird; Bohlenquerschnitt 67 × 195 mm²

imens tested in static bending were subdivided into small sticks to reveal the MOE variation over the cross section of the specimens. Examples of typical distribution patterns of density and calibrated E_{dyn} are given in Figure 8 to Figure 10.

Figure 8 gives an example for a spruce board with relatively narrow growth rings, medium to high mean density, a decrease of density toward the pith, and a marked gradient of the calibrated dynamic MOE values of the sticks from the sapwood to the pith. This specimen re-

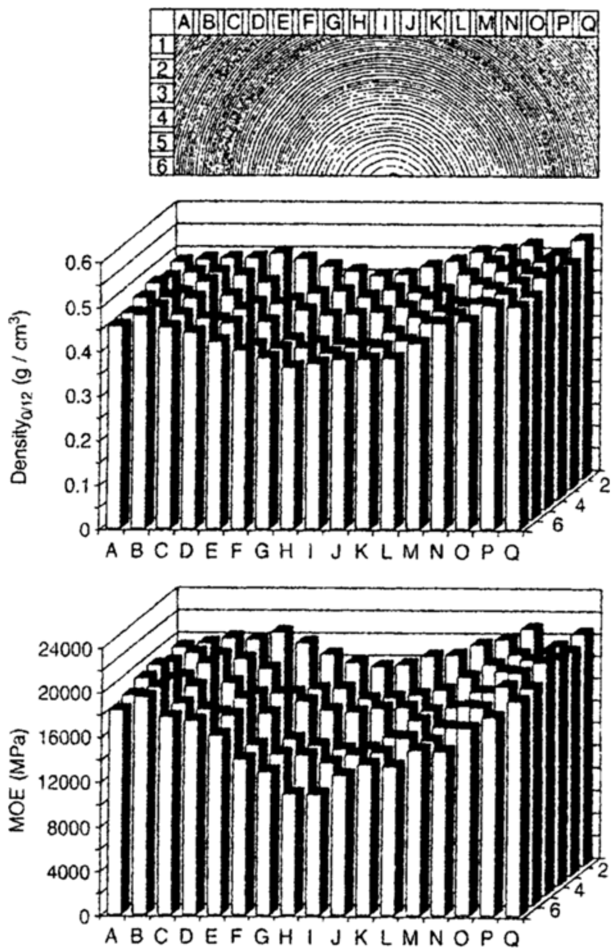


Fig. 8. Distribution of wood density (m.c. = 12%) and MOE (calibrated E_{dyn}) in the clear section of board no. 21
Bild 8. Verteilung der Rohdichte (u = 12%) und des kalibrierten dynamischen E-Moduls (E_{dyn}) über den astfreien Querschnitt der Bohle 21

vealed the highest E_{edge} value and one of the highest E_{edge}/E_{flat} ratios of all specimens studied. The data point for this specimen lies on the uppermost end of the respective regression line in Figure 5.

The dark latewood zones on the right hand side of the clear specimen of board 21 (Figure 9) indicate compression wood associated with relatively high density but low calibrated E_{dyn} values in the particular zone. Compared with the other board specimens, the E_{dyn} distribution is relatively homogenous. The clear specimen of board 21 displayed one of the lowest E_{edge} values of all boards tested and the second lowest E_{edge}/E_{flat} ratio of the bigger boards and hence, falls on the lower end of the respective regression line in Figure 5.

In Figure 10 (knotty specimen of board 21), the marked influence of radially-oriented knots on the calibrated E_{dyn} is illustrated. The density distribution over the latter board specimen does not differ markedly from that of the clear specimen of board 21.

The evaluation of the E_{dyn} distribution over the cross-cut section of the specimens in connection with the regression analysis illustrated in Figure 5 indicates that boards with a high E_{edge} tended to have a marked MOE-gradient over the cross section while those boards revealing a low E_{edge} value had a relatively homogenous distribution of MOE over the cross section. Results obtained by Boström (1994) show

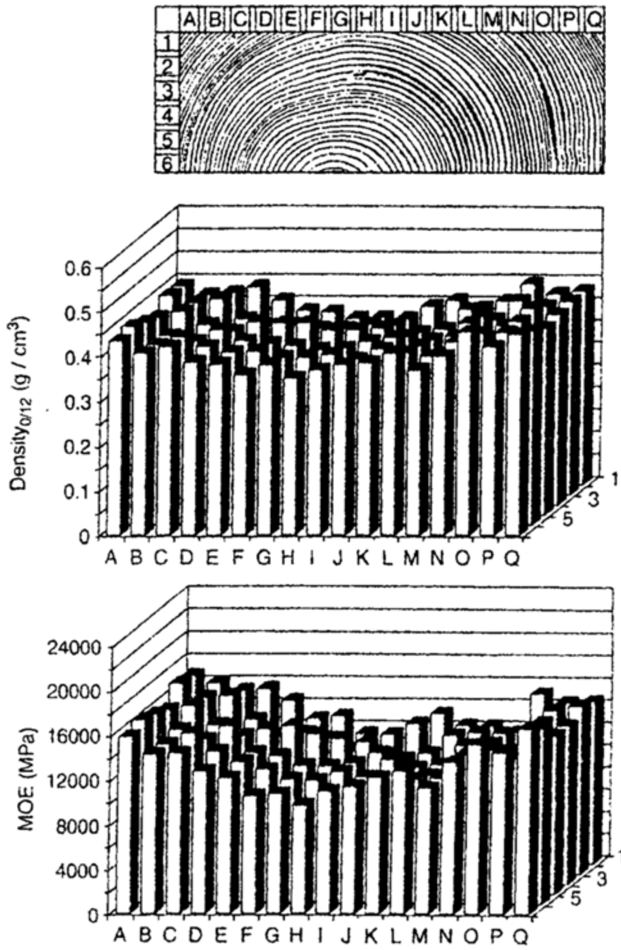


Fig. 9. Distribution of wood density (m.c. = 12%) and MOE (calibrated E_{dyn}) in the clear section of board no. 21
Bild 9. Verteilung der Rohdichte (u = 12%) und des kalibrierten dynamischen E-Moduls (E_{dyn}) über den astfreien Querschnitt der Bohle 21

the same tendency. The sawing pattern and the log-size/board-size ratio of the timber in this study lead to an increase of MOE toward both edges of the boards favouring high edgewise bending MOE values rather than flatwise bending MOE. In edgewise bending, both the tension and the compression zone of a specimen with a pronounced MOE gradient consist of mature wood with relatively high MOE and render a high E_{edge}, while in flatwise bending the relatively weak juvenile portion of the log leads to a relatively low MOE in compression or in tension of the wood fibres and consequently to a relatively low E_{flat}.

4.3 Calculated flatwise and edgewise MOE of the board specimens

Based upon the calibrated E_{dyn} values of the $9 \times 9 \times 300$ mm^3 sticks the total edgewise and flatwise MOE values, $E_{edge\ calc}$ and $E_{flat\ calc}$, have been calculated according to

$$E_{calc} = \frac{\sum_{i=1}^{n} E_i I_i}{\sum_{i=1}^{n} I_i} \qquad \text{(Eq. 6)}$$

where E_i is the MOE of a stick and I_i is the moment of inertia of the stick's cross section in relation to the neutral axis (Figure 3). The calculated MOE values are presented in Table 3 in comparison with the actual values obtained from the bending tests.

The comparative MOE analysis for the clear specimens proved close correspondence of $E_{edge\ calc}$ and E_{edge} determined in static four-point bending, whereas the correspondence between $E_{flat\ calc}$ and E_{flat} determined in static three-point bending was relatively poor. The $E_{edge\ calc}/E_{edge}$ ratios were nearly 1.0 for both board dimensions, while the $E_{flat\ calc}/E_{flat}$ ratios were 1.14 and 1.27, respectively, which means that the actual MOE of the boards of 45×170 mm^2 was about 14% lower than the calculated MOE; for the boards of 67×195 mm^2, the difference was 27%, twice as high as for the smaller ones.

Regression analysis for boards of both dimensions rendered functions of very high coefficients of determination ($R^2 = 0.90$ to 0.99) for actual and calculated values of edgewise and flatwise MOE, respectively (Figure 11, Figure 12). Consequently, the deviation of E_{flat} from $E_{flat\ calc}$ is a constant factor, independent of the absolute level of the MOE measurement. This deviation may be due to the influence of shear deformation on the total E_{flat} measured in the three-point bending test.

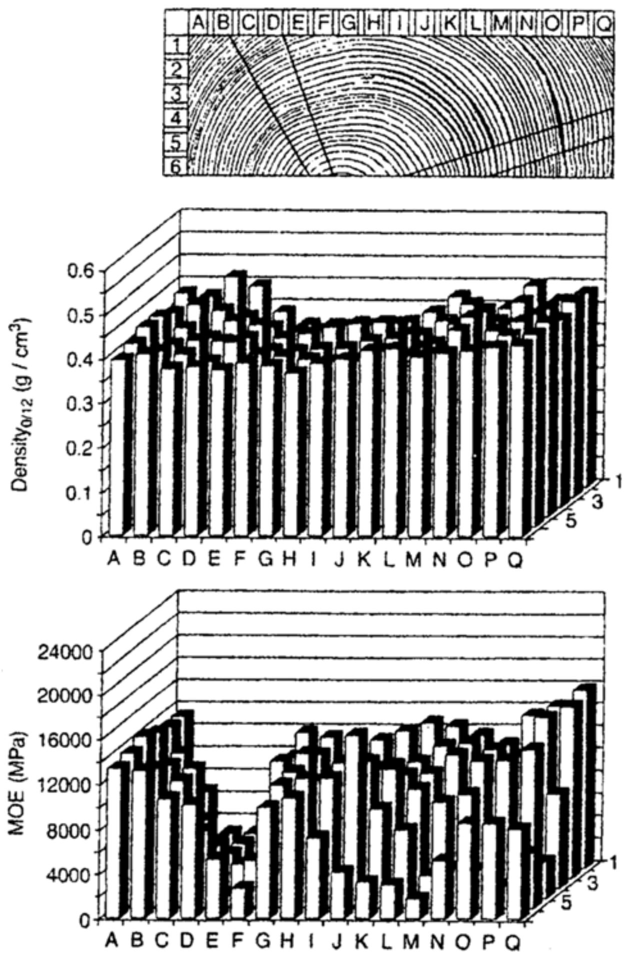


Fig. 10. Distribution of wood density (m.c. = 12%) and MOE (calibrated E_{dyn}) in the knotty section of board no. 21
Bild 10. Verteilung der Rohdichte (u = 12%) und des kalibrierten dynamischen E-Moduls (E_{dyn}) über den astigen Querschnitt der Bohle 21

Table 3. Calculated and actual MOE values of clear and knotty board specimens
Tabelle 3. Berechnete und gemessene E-Modulwerte von astfreien und astigen Proben

Board	E_{flat} [N/mm^2]	$E_{flat\ calc}$ [N/mm^2]	$\frac{E_{flat\ calc}}{E_{flat}}$	E_{edge} [N/mm^2]	$E_{edge\ calc}$ [N/mm^2]	$\frac{E_{edge\ calc}}{E_{edge}}$	$\frac{E_{edge\ calc}}{E_{flat\ calc}}$
Board size 45 × 170 mm^2, clear specimens							
01	11700	13200	1.13	13650	13650	1.00	1.03
01	12500	14700	1.18	14750	15750	1.07	1.07
08	11850	14000	1.18	14850	15200	1.02	1.09
09	14450	16300	1.13	16050	17100	1.07	1.05
10	14950	17000	1.14	19950	18950	0.95	1.11
14	12400	14100	1.14	16300	15500	0.95	1.10
19	11200	12550	1.12	12700	12650	1.00	1.01
20	12250	13850	1.13	14050	14350	1.02	1.04
Average	12650	14450	1.14	15300	15400	1.01	1.06
Board size 67 × 195 mm^2, clear specimens							
21	10600	13200	1.25	13950	14150	1.01	1.07
23	8800	10650	1.21	11200	11450	1.02	1.08
25	12550	15700	1.25	17650	16850	0.95	1.07
34	13200	17050	1.29	21000	18650	0.89	1.09
35	12700	16900	1.33	18750	18700	1.00	1.11
Average	11550	14700	1.27	16500	15950	0.97	1.09
Board size 45 × 170 mm^2, knotty specimens							
01	11100	10050	0.91	13650	12100	0.89	1.20
08	10850	9250	0.85	13250	11400	0.86	1.23
14	11300	10750	0.95	13900	9550	0.69	0.89
Average	11080	10020	0.90	13600	11020	0.81	1.11
Board size 67 × 195 mm^2, knotty specimen							
21	9400	8700	0.93	12750	9300	0.73	1.07

Comparing $E_{flat\ calc}$ with $E_{edge\ calc}$, (Table 3) no clear difference between the two board dimensions can be found. Overall, the $E_{edge\ calc}$ values lie 1 to 11% above $E_{flat\ calc}$. For the smaller boards, $E_{edge\ calc}$ lies on average 6% higher than $E_{flat\ calc}$. For the bigger boards, the difference amounts to 9%. These differences correspond closely with data obtained by Burger and Glos (1995). They may be explained with the systematic variation of the MOE over the board cross section as exemplified in Figure 8 to Figure 10.

The MOE values calculated for the four specimens of knotty timber deviated considerably from the respective MOE measured in static bending (7 to 31% difference). The position of the knots exerts a pronounced influence on the results of the calculation, especially for E_{edge} which results in a variation of the $E_{edge\ calc}/E_{flat\ calc}$ ratios that is much wider as compared to the clear specimens. For instance, in specimens 14 and 21 edge knots lead to calculated edgewise MOE values which are distinctly lower than the actual static MOE. Recalling the fact that E_{edge}/E_{flat} ratios calculated on the basis of static bending tests were fairly similar for clear and knotty specimens (Table 2), it becomes obvious that the knot influence on MOE was overrated in the calculation model.

5 Discussion

With regard to knot size and growth ring width, two visual grading criteria of major importance in the German DIN 4074, most of the boards tested in this study fulfilled the requirements of S 13; the highest timber strength class in visual grading. In this respect, the material studied was of relatively good quality which has to be considered when interpreting the results. The flatwise MOE values determined for the boards of this study lie between about 9000 and 15000 N/mm^2 or on average about 1000 to 2000 N/mm^2 higher than the design value for spruce timber in structural application according to class S 13 in DIN 1052.

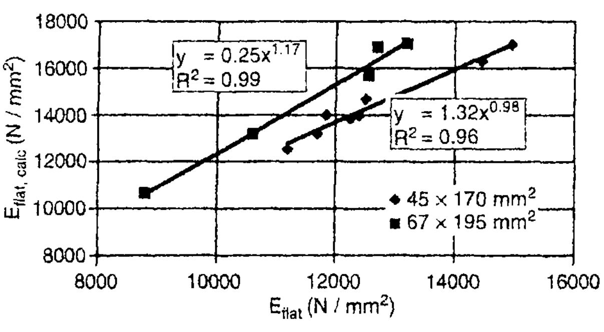


Fig. 11. Relationship between $E_{flat\ calc}$ and E_{flat} determined in three-point loading
Bild 11. Zusammenhang zwischen dem berechneten Flachkant-E-Modul ($E_{flat\ calc}$) und E_{flat} bestimmt im Drei-Punkt-Biegeversuch

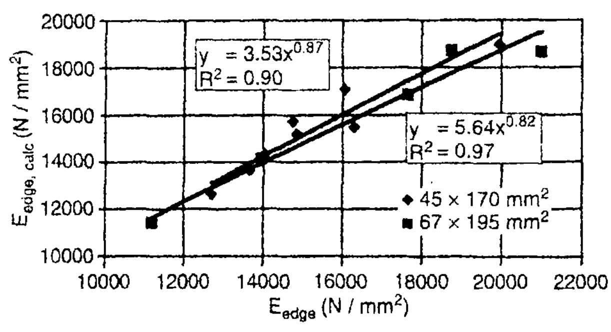


Fig. 12. Relationship between $E_{edge\ calc}$ and E_{edge} determined in four-point-loading according to EN 408
Bild 12. Zusammenhang zwischen $E_{edge\ calc}$ und E_{edge} bestimmt im Vier-Punkt-Biegeversuch nach EN 408

Static bending tests only revealed a small decrease of the modulus of elasticity due to the presence of knots in the board specimens. A knot-area-ratio (KAR) of 0.35 actually lead to a reduction of the MOE of about 11% in comparison with the knot-free reference specimen (specimens no. 9 and 23, Table 2). This corresponds well with data obtained by Samson and Blanchet (1992) while Görlacher (1989) calculated a MOE reduction of about 66% employing a statistical model proposed by Glos for the same KAR value. Such discrepancies between the results obtained in different studies indicate that the actual size, number, distribution, and structure of knots must influence the MOE measurement to a considerable extent. Consequently, direct comparisons of MOE values of knotty timber specimens, even with similar KAR value, obtained in different studies are hardly feasible. In this study, only specimens with groups of relatively small knots were tested in comparison with clear specimens. In other studies, a certain KAR may have been due to isolated big knots which may have much greater influence on MOE than groups of small knots.

The increase of the E_{edge}/E_{flat} ratio with decreasing knot-area-ratio indicates that the knots may have reduced the MOE variation over the cross section or they may have reduced shear deformation of the timber in the three-point bending test. Detailed studies on this subject are needed.

Steiner's formula rendered reliable results in estimating total MOE values of clear boards on the basis of calibrated E_{dyn} values for the small sticks. Varying elastic moduli due to compression wood, juvenile wood, growth ring structure, and density in the clear specimens were correctly represented in the model and hence, rendered calculation results matching the actual MOE values relatively precisely. A correct prediction of the effect of knots on the board MOE was not feasible with this formula. The formula failed in predicting the effect of weak zones of knots in the cross section because relative to the length of the sticks of 300 mm, the knot zones with a low MOE represented much larger a portion of the specimen as compared to the gauge length over which the elastic deformation was recorded on the full-sized boards. Consequently, the influence of the weak knot zone on the ultrasonic pulse velocity in the stick was distinctly higher as compared to the situation in the entire boards. A second reason for the inaccuracy of the prediction is that the adherence of the knot zones to the surrounding wood fibres was disregarded (see Colling 1990). The wood fibres surrounding the relatively weak knot zones absorb the stresses to a limited stress level very effectively.

The E_{edge}/E_{flat} and $E_{flat}/E_{flat\ calc}$ ratios varied widely between individual boards, generally increasing with increasing board thickness. To evaluate the systematic deviation of E_{edge} and $E_{flat\ calc}$ from E_{flat}, especially for different board dimensions, the shear deformation in the three-point flatwise bending test and possible other causes have to be analysed. In the edgewise four-point bending test, E_{edge} resulting from a pure bending moment is determined while in the three-point flatwise bending test, board deflection due to shear stress, characteristically increasing with increasing board thickness, reduces the E_{flat} record. In the three-point bending tests conducted in this study, board thickness and shear deformation were not considered when calculating E_{flat}.

For compensation of deflection due to shear stress in three-point flatwise bending, E_{flat} is usually corrected according to Equation 7 (e.g. Görlacher 1991).

$$E_{corrected} = E_{flat} \cdot \left(1 + s \cdot \left(\frac{d}{L}\right)^2 \cdot \frac{E}{G}\right) \quad [\mathrm{MPa}] \qquad \text{(Eq. 7)}$$

$E_{corrected}$ = MOE free from shear deformation
E = MOE
s = form factor (= 1.2 for rectangular boards)
L = span
d = board thickness
G = shear modulus

According to Ehlbeck (1969) the E/G ratio for German structural spruce timber, quality class II according to the former DIN 4074, lies between 22.5 and 32.3. Employing an E/G ratio of 30 in a calculation of $E_{corrected}$ for the boards tested in this study, shear deformation would account for 9 to 20% of the difference between calculated and actual flatwise MOE which amounted to 14 and 27%, respectively, for the small and the big boards. Employing an E/G ratio of 20, as presumed in DIN 1052, shear deformation would account for 6 and 13% of the difference between E_{flat} and $E_{flat\ calc}$ for the smaller and the bigger boards, respectively. The remainder must be attributed to compression perpendicular to the grain at the supports which is measured as deflection in the three-point bending test.

Definitely, the systematic influence of the shear deformation and the compression at the supports on the accuracy of the MOE determination in flatwise and edgewise bending does not explain the wide variation of the E_{edge}/E_{flat} ratio between the boards. This variation must be attributed to the inhomogeneous MOE distribution over the timber cross section.

An attempt was made to calculate the E/G ratio for the boards examined in this study: Assuming that $E_{edge\ calc}$ and $E_{flat\ calc}$ of the clear specimens represent the actual MOE independent of shear deformation, $E_{corrected}$ may be replaced by $E_{flat\ calc}$ (or $E_{edge\ calc}$) in Equation 7 to estimate the E/G ratio individually for each specimen. The ratio varies greatly between 30 and 60 but lies in the order that is presumed in the relevant standards and was obtained in former studies (e.g. Ehlbeck 1969). The variation of the E/G ratio limits the accuracy of any MOE assessment in continuous three-point bending tests in strength grading machines. These results indicate that the deformation of thicker boards due to shear stress in flatwise three-point-bending in strength grading machines is the major cause for an inaccurate estimation of the edgewise MOE. The effect of growth ring structure, juvenile wood, and pith position on the relationship between flatwise and edgewise MOE is clearly inferior to the effect of shear deformation. The total effect of these structural features of the wood on MOE seem to be correctly reflected in the grading results. Within the frame of this study, it was impossible to develop a mathematical model describing the individual influences of these structural features and their distribution over the cross section separately.

6
Conclusions

With regard to improvements in mechanical timber strength grading, the following conclusions are drawn:

- The difference between edgewise MOE according to EN 408 and flatwise MOE determined in a three-point loading test depends on shear deformation, knots, and the natural variation of MOE over the timber cross section.

- The optical detection of knots in boards should be optimised. Further research should be focused on the effect of knots on strength properties as it may differ distinctly from the influence on MOE.
- Density and MOE varied considerably over the timber cross section. This variation can be linked to the sawing pattern and to the log size/board size ratio. Consequently, the sawing pattern may also be considered in mechanical strength grading with regard to growth ring structure and pith position.

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